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Analysis and characterization of wind-solar-constant torque spring hybridized model

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Abstract Solar and wind are the most promising renewable energy resources. But their unpredictable and varying nature prevents them from being used as the sole resource for power generation. This paper presents a model of wind and solar thermal hybrid power plant with a spring storage system which is expected to play an efficient role in combating with the drawbacks related to renewable power generation. In the proposed scheme, wind energy is harnessed by a hybrid vertical axis wind turbine, solar energy is utilized by a Stirling engine, and the surplus energy is stored in a winding spring. The paper discusses the working methodologies and analyses the performance of such 2.6 kW hybrid power plant model. It has been observed that the plant is capable of consistently generating 50% of its rated capacity irrespective of limitations in solar and wind resources.

Keywords hybrid vertical axis wind turbine, Stirling engine, solar-thermal energy, wind energy, constant torque spring

1 Introduction

More than 90% of the electricity in the world is generated by using fossil fuels. However, reserves of these fuels are limited. According to Ref. [1], coal—the most lasting fossil fuel, will last for 118 years. Moreover, combustion of fossil fuels release green house gases like carbon dioxide (CO₂), which have adverse effect on the environment and create environmental disasters like global warming.

The most viable alternative to fossil fuels is renewable energy sources as they are eco-friendly, easily available and cost free. But renewable energy sources are character-

ized by intermittency and unpredictability. These drawbacks encouraged the hybridization of two sources for power generation. Different works have been done on hybridization of different renewable energy sources [2–14]. Among them, the most preferred sources are the solar and wind energies as they are the most widely spread [4–12]. The majority of solar-wind hybrid plant uses photovoltaic (PV) array and horizontal axis wind turbine (HAWT) for power generation [5–8,10–12]. The flow of wind is random and hence the HAWT requires a “yaw mechanism”. On the contrary, vertical axis wind turbine (VAWT) does not require this mechanism and generates power irrespective of wind direction. Where wind varies frequently in direction and velocity, VAWT is more advantageous than HAWT [14]. In Refs. [15] and [16], a hybrid vertical axis wind turbine (HVAWT) which operates on both drag and lift force has been described. In the former case, the power generated by the drag type blade has been ignored when lift type blades operate independently. In the later case, a HVAWT for hydel power generation has been illustrated where the two types of blades are kept fixed to each other in a common shaft. However, this type of fixed arrangement limits the benefits of straight bladed turbine reducing the power generation. The limitations of the HVAWT have been eliminated in the proposed plant comprising of a HVAWT, a Stirling engine based solar thermal system and a spring storage arrangement.

Stirling engine was first developed by Robert Stirling in 1816 [17]. Though it was not admired so much at the beginning, it enjoyed remarkable popularity later on. Stirling engine operates on the principle of thermal expansion and compression. It is an external combustion engine [18,19] which is cheap and pollution free. It also has good efficiency with less noise but is not able to generate immediate power. A number of scientists worked on Stirling engine for its development in the last few decades [17,20,21]. In this paper, an Alpha type Stirling engine is employed for generating power from the heat of the sun. The Schmidt theory is adopted for modeling and analyzing the engine as it is more comprehensive [22].

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The engine in the scheme is run by the heat provided by a specially designed Fresnel lens capsule. The capsule is made up of a number of small Fresnel lenses. The lenses have characteristics of concentrating solar radiation resulting in the rise of their focal point temperature. This phenomenon has been adopted for heating objects in many applications [23–26].

The storage system is an inevitable part of a power plant. A good storage system can eliminate the limitations caused by the intermittency and stochastic nature of renewable energy resources to a great extent. The predominant storage systems like super capacitor, super inductor and flywheel operate for a very short period of time, typically less than 6 s [27]. The most preferred storage device, (i.e. battery), also has limitations such as sensitivity to environment, life span dependency on operating temperature, large charge to discharge time ratio [28], etc. Here, one of the oldest means of storage, (i.e. a spring), has been used for storing energy which is expected to trim down the shortcomings of prevailing storage system considerably. The life span of the spring and amount of energy that can be stored depend mainly on the material used. In 2009, a spring made up of carbon nano tube (CNT) was developed which has high modulus of elasticity and strong network of carbon-carbon bond [29]. This CNT spring can store energy that is comparable to lithium ion batteries [29]. For the sake of simplicity, a metallic constant torque spring is considered in the proposed system.

2 Plant design and description

The plant is a complete system of three sub-systems: wind

sub-system, solar sub-system and storage sub-system. Figure 1 shows the block diagram of the plant.

2.1 Wind sub-system

2.1.1 Hybrid vertical axis wind turbine model

The hybrid wind turbine is composed of a Savonius rotor (S-blade) and a Darrieus rotor (H-blade). The S-blade rotor is coupled to the storage system and the H-blade rotor to the generator. Thus, a part of the energy generated from wind gets stored and the rest drives the generator while increasing the efficiency of the turbine. The S-blade is made by cutting a cylinder into two symmetric halves and then moving the semi-cylinders sideways so that the cross section resemble the letter ‘S’. There are two sets of S-blade, placed 90° apart. If C_{ps} is the coefficient of power for the S-blade, A_s is the area of the blade, ρ is the air density and V is the wind velocity, then the power generated by S-blade (P_s) will be given by

$$P_s = \frac{1}{2} \rho A_s V^3 C_{ps}. \quad (1)$$

The H-blade is the cambered straight blade which is operated by the lift force of wind. There are three H-blades, placed 120° apart below the S-blades. The power generated by the H-blade (P_h) is given by

$$P_h = \frac{1}{2} \rho A_h V^3 C_{ph}, \quad (2)$$

where A_h is the swept area of the H-blade, C_{ph} is the power coefficient for the H-blade.

Wind power (P_w) is given by

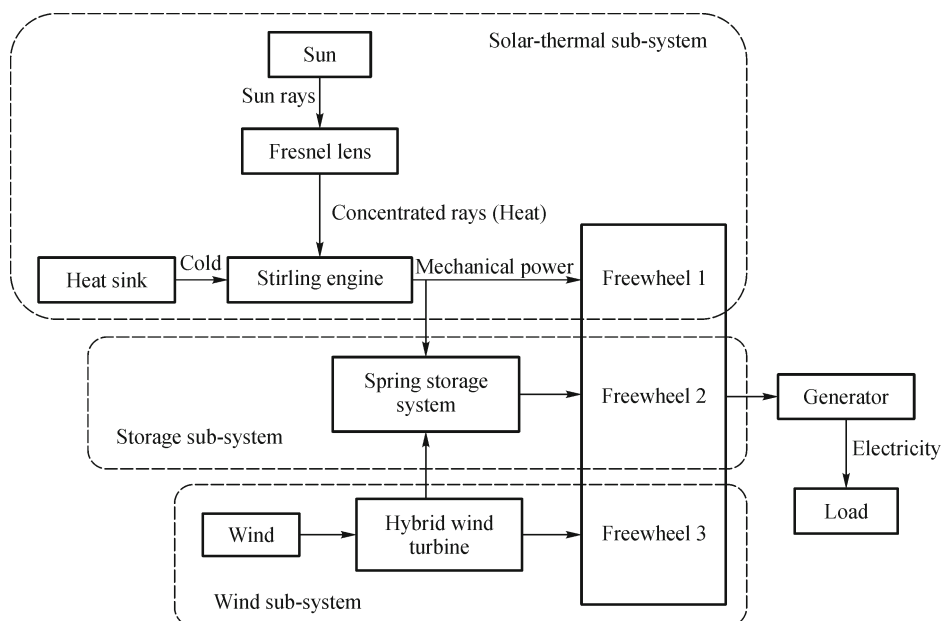


Fig. 1 Block diagram of the hybrid plant

$$P_w = \frac{1}{2} \rho V^3 (A_s + A_h), \quad (3)$$

The power generated by the HVAWT (P_t) can be calculated by Eq. (4). P_t equals to the S-blade power when wind speed is below 4 m/s (cut-in speed of H-blade) and equals to the H-blade power when wind speed is above 4 m/s.

$$P_t = \begin{cases} \frac{1}{2} \rho A_s V^3 C_{ps} & V < 4, \\ \frac{1}{2} \rho A_h V^3 C_{ph} & V \geq 4. \end{cases} \quad (4)$$

There are two types of turbines having two tip speed ratios (TSRs). The overall TSR of the turbine can be obtained by

$$\lambda = \begin{cases} \frac{\omega_s R_s}{V} & V < 4, \\ \frac{\omega_h R_h}{V} & V \geq 4, \end{cases} \quad (5)$$

where ω_s is the angular velocity of the S-blade, ω_h is the angular velocity of the H-blade, R_s is the radius of the S-blade, and R_h is the radius of the H-blade. The starting torque (t_s) of the HVAWT is provided by the S-blade and can be calculated by

$$t_s = \frac{P_s}{\omega_s N}, \quad (6)$$

where N stands for turbine speed.

2.1.2 Aerodynamics of the turbine

The aerodynamics of the turbine with a complete set of the

S-blade and a single H-blade at four different positions (0° , 90° , 180° and 270°) is illustrated in Fig. 2. A single H-blade is shown in the figure as remaining two blades will follow the same path. Two basic forces, i.e. the drag force and the lift force, are created by the blades. The S-blade rotor provides a high drag to overcome the inertia of the turbine, making itself start at a low wind speed. The H-blade creates a high lift, thus generating more power at the rated wind speed.

The force can be split into two components. One is the velocity of the H-blade relative to the shaft, having a magnitude equal to the product of rotational speed (ω) and its radius (R_d). The other is the wind velocity (V), which is assumed to be constant in one direction. The resultant velocity (V_R) is the effective velocity of the wind experienced by the H-blade. The angle between this resultant velocity and the chord of the H-blade is called the angle of attack (α). Whenever the phase angle (θ) is 90° and 270° , the angle of attack is 0° . At these positions, only the drag force (D) exists. The drag force is always parallel to the resultant wind velocity. The lift (L) is perpendicular to the drag force and is created by the difference in pressure between the top and bottom surface of the H-blade. It occurs whenever the angle of attack is not equal to zero. The lift force is always perpendicular to the drag force and thus to the resultant direction of wind.

2.2 Solar thermal sub-system

2.2.1 Stirling engine design

Stirling engines are external combustion engines which can function by using a wide variety of fuel sources such as a combustible gas, nuclear head, or solar energy. The

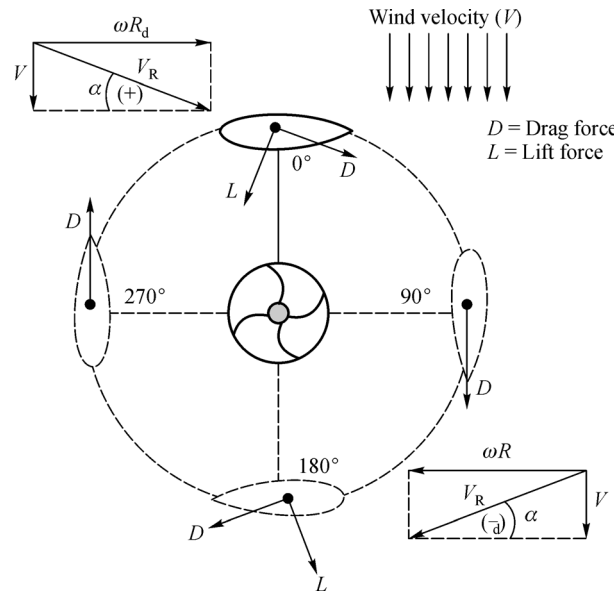


Fig. 2 Aerodynamics of the turbine

Stirling cycle is a reversible cycle which closely follows the Carnot principal, making it highly efficient.

Schmidt theory is the simplest and useful method for Stirling engine design. In this paper, the same theory is adopted for designing the engine. The governing equations for the Stirling engine are given below. The symbols and their meanings used are given in Notations.

$$t = \frac{T_c}{T_e}, \quad (7)$$

$$v = \frac{V_{sc}}{V_{se}}, \quad (8)$$

$$X_{de} = \frac{V_{de}}{V_{se}}, \quad (9)$$

$$X_{dc} = \frac{V_{dc}}{V_{se}}, \quad (10)$$

$$X_r = \frac{V_r}{V_{se}}, \quad (11)$$

$$a = \tan^{-1} \frac{v \sin D_x}{t + \cos D_x}, \quad (12)$$

$$b = \sqrt{t^2 + 2v \cos D_x + v^2}, \quad (13)$$

$$S = t + 2tX_{de} + \frac{4tX_r}{1+t} + v + 2X_{dc}, \quad (14)$$

$$c = \frac{b}{S}, \quad (15)$$

$$W_e = i_s \times L_a \times z, \quad (16)$$

$$M_g = \frac{P_m V_{se} \sqrt{S^2 - b^2}}{2R_f T_c}, \quad (17)$$

$$P_m = \frac{W_e (1 + \sqrt{1 - c^2})}{V_{se} \pi c \sin a}, \quad (18)$$

$$P_e = \frac{P_m \sqrt{1 - c^2}}{1 - c \cos(x - a)}, \quad (19)$$

$$W_i = W_e + W_c, \quad (20)$$

$$P_o = \frac{n \times W_i}{60}, \quad (21)$$

$$t_e = \frac{P_o}{\omega n}, \quad (22)$$

$$T_l = \sqrt[4]{\frac{i_s}{S \times A}}. \quad (23)$$

2.2.2 Operation of Stirling engine with Fresnel lens

The complete arrangement of a Stirling engine along with the Fresnel lens capsule is demonstrated in Fig. 3. Generally, a solar based system needs a tracking arrangement to capture perpendicular radiation for better efficiency. In this arrangement, as shown in Fig. 3, a capsule of multiple Fresnel lenses are used to enhance the efficiency. The Fresnel lens collects the solar radiation available in its surface area and concentrates it at its focal point. Therefore, the focal point of the lens has thermal energy equivalent to the solar energy at its surface area. The expansion chamber of the Stirling engine is kept inside this capsule. The system is designed in such a way that the sun is always perpendicular to at least one of the lens whose

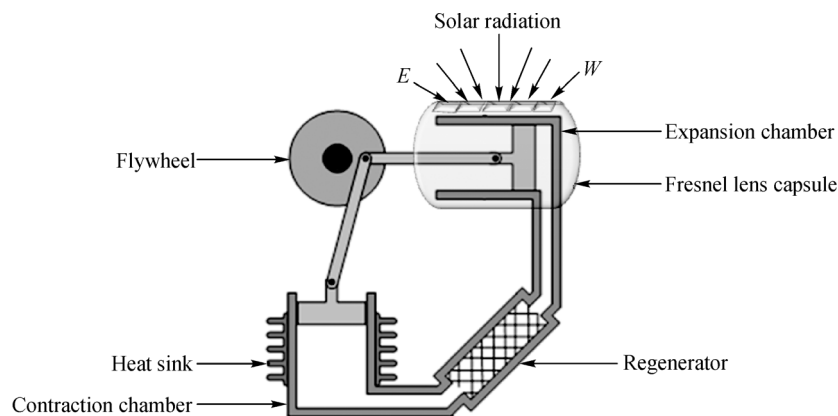


Fig. 3 Stirling engine with Fresnel lens capsule

focal point lies on the engine chamber. Hence, at any position of the sun, the capsule is capable of providing a steady operating temperature for the engine.

The heat absorbed by the expansion chamber of the engine gets transferred to the fluid (air), as displayed in Fig. 4. The air inside the chamber expands and pushes the piston outward, thus rotating the flywheel. The rotation of the flywheel draws the piston in the contraction chamber outward. The expanded hot fluid passes to the contraction chamber via the regenerator where some of the heat is absorbed, thus the fluid gets pre-cooled.

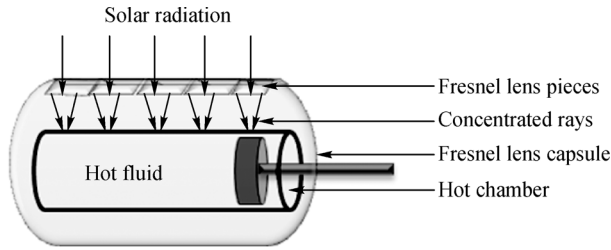


Fig. 4 Fresnel lens capsule with expansion chamber of Stirling engine

In the contraction chamber, the heat is reduced from the fluid, making it cool. This squeezes the volume of the fluid, and as a result, a vacuum is created which sucks the piston in. The simultaneous suction and rotation of the flywheel moves the contracted fluid from the contraction chamber to the expansion chamber through the regenerator. In this trip, the regenerator pre-heats the fluid by releasing the previously absorbed heat.

2.3 Storage sub-system

A constant torque spring is used to store the surplus energy of the system. A constant torque spring with a brand name of 'Contorque' of the Vulcan Spring and Mfg. Co. is shown in Fig. 5 [30]. During storage of energy, the spring wound on to the larger mandrel. The shaft of this mandrel consists of two free wheels which are connected to the HVAWT and the flywheel of the Stirling engine. When energies of both the driving systems are less than the energy stored in the storage system, the spring recoils itself to the smaller mandrel, releasing the stored energy. The stored energy is transferred to the shaft of the generator via the second freewheel, coupled to the shaft of the smaller mandrel and the generator.

Expression for torque in contorque spring is given by

$$T = \frac{Eb_s t_s^3}{24} r_o \left(\frac{1}{r_n} + \frac{1}{r_o} \right), \quad (24)$$

where E represents Young's modulus, b_s symbolizes the width of the spring; t_s signifies the thickness of the spring, r_n represents the natural radius of the spring, and r_o is the radius of the output mandrel.

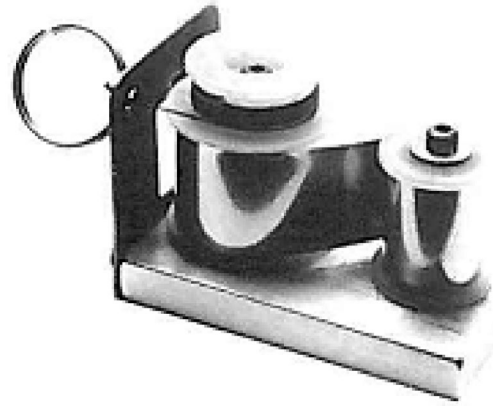


Fig. 5 Contorque spring

2.4 Freewheel

Freewheels play a pivotal role in this hybrid plant. There are three freewheels on the shaft of the generator coupled to the Stirling engine, the storage spring and the HVAWT respectively. They aid the transfer of the power from the sub-systems to the generating shaft. A simple freewheel consists of a ratchet wheel (having saw-tooth groove in the inner rim), a movable pawl pivoted at one end in a fixed arrangement and a spring lifting up another end of the pawl. The complete structure of the freewheel is depicted in Fig. 6. When solar energy is greater than wind energy, the Stirling engine rotates freewheel 1 faster than freewheel 3—rotated by the HVAWT. The pawl of freewheel 1 gets stuck in the grooves of the ratchet wheel and consequently, the generator shaft starts rotating with it. Since the fixed arrangement of the three freewheels are fixed to the common generator shaft, the faster movement of the shaft results in the compression of the pawl of other two freewheels and thus, the generator shaft is rotated by the stronger sub-system i.e. the solar sub-system.

There is one more freewheel on the HVAWT which separates the H-blade from the S-blade when wind speed is greater than 4 m/s. When the fixed arrangement rotates along the shaft of the S-blade in the direction shown in Fig. 6, the pawl gets stuck in the groove of the ratchet wheel. The shaft of the H-blade is fixed to the ratchet wheel. Thus the motion of the S-blade rotates the H-blade. The H-blade rotates faster than the S-blade by pressing the pawl toward the fixed arrangement.

The freewheels on the storage sub-system are different from others. The two freewheels on the larger mandrel of the storage spring facilitate the storage of energy available from the weaker sub-system. There is no spring beneath the pawls in these freewheels. Rather, the pawls are so built that they can bend through the middle and one end is rigidly fixed to the fixed arrangement on the shaft. The pawls of both freewheels are interconnected in a manner that only one pawl can bend at any instant and the other

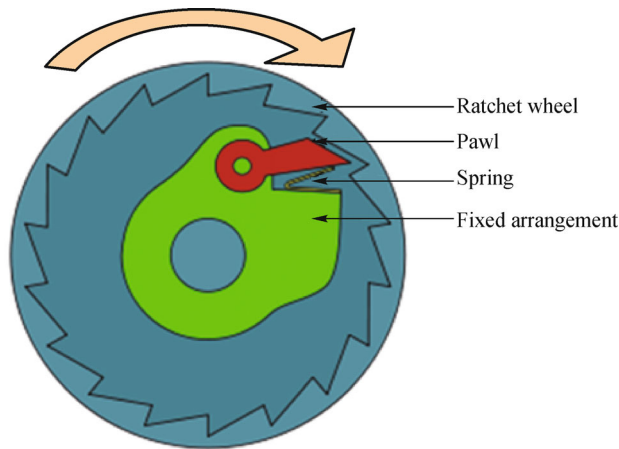


Fig. 6 Freewheel

will remain straight for that period. These freewheels are coupled to the two subsystems i.e., solar and wind. When any of the subsystem is rotating faster, the pawl in the respective freewheel bends and lets the ratchet wheel to pass by. At the same time, the pawl of the weaker system gets stuck in the groove of the ratchet wheel and the energy gets transferred to the storage system.

3 Analysis of the results

A 2.6 kW wind-solar-constant torque spring hybridized model comprising 1.3 kW wind sub-system and 1.3 kW Stirling engine based solar sub-system has been developed in LabVIEW 8.6. The assumptions for design parameters of the plant are given in Appendix. The block diagram for simulation of the complete plant is presented in Fig. 7.

3.1 Powers delivered by system components

Figure 8 shows the power given out by the proposed hybrid power plant in a period of 24 h. It is clearly observed from Fig. 8 that at any instant, the generator is driven by the complementary contribution of the storage and the potent system (either wind or solar sub-system) to supply constant mechanical power of 1.3 kW. At the very moment, power generated by the weaker sub-system is stored in the spring. Four instants have been taken into account for the better analysis of the results in Fig. 8.

Instant 1: At this instant, there is no solar insolation. The mechanical power necessary for generating the rated output power is supplied by the HVAWT and the spring. Hence the output power is the contributions of the wind and storage sub-systems.

Instant 2: The power from both solar and wind sub-systems are available; the engine power is increasing whereas wind power is decaying. The moment when solar power overcomes wind power, the Stirling engine takes

over the HVAWT to drive the generator. The deficit power is provided by the storage system to generate the rated power. The wind power generated in the mean time gets stored in the spring.

Instant 3: In this period, solar resource is high; the Stirling engine alone is driving the generator at this moment. The input from the storage system is zero. The small amount of power generated by the wind sub-system is stored in the constant torque spring.

Instant 4: This period describes a situation when power from both wind and solar sub-systems are meager. In this condition, the spring drives the generator and a constant rated output is availed.

The result obtained from the simulation depicts that a constant power is available all day irrespective of the limitations of the solar and wind resources.

3.2 Starting torque at rated and below rated wind speed

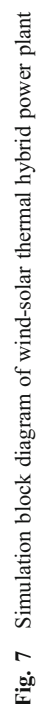
Figure 9 shows the starting torque characteristic of the HVAWT at rated (10 m/s) and below rated wind speed (8 m/s). At standstill condition, the torque is found to be 178 N·m/rad and 100 N·m/rad at rated and below rated wind speed. The torque developed at halt condition is due to the solidity of the S-blade resulting in self starting of the rotor at a low wind speed. As the rotor starts moving, the torque begins to decline which exemplifies the inverse relationship between the torque and the speed. At rotor speed of 90 r/min, the torque is observed to be 43 N·m/rad for wind speed of 8 m/s and 76 N·m/rad for the rated wind speed.

3.3 Phase angle vs. angle of attack of H-blade

Figure 10 shows the change in the angle of attack caused by the rotation of the blade i.e. due to change in phase angle. It is assumed that, initially blade 1 is making an angle of 0° with the direction of wind i.e. the phase angle is 0°. Since each blade is placed 120° apart, therefore at the initial condition, blades 2 and 3 are making an angle of +120° and -120° respectively with the wind direction. At this phase angle, the resultant angle of attack is 0°. After every 120° rotation, each blade takes the position of the next blade. As the phase angle increases, the angle of attack also increases. At phase angle of 60°, the blade position with respect to the flow of wind reverses and hence the angle of attack of blade 2 becomes negative. Eventually, the resultant angle of attack also becomes negative. Further rotation of the blades results in a rise in resultant angle of attack.

3.4 H-blade power coefficient vs. TSR at different wind speed

The power coefficient (C_{ph}) against TSR (λ) of the H-blade for the rated and the below rated wind speeds are depicted in Fig. 11. For the rated wind speed of 10 m/s, the



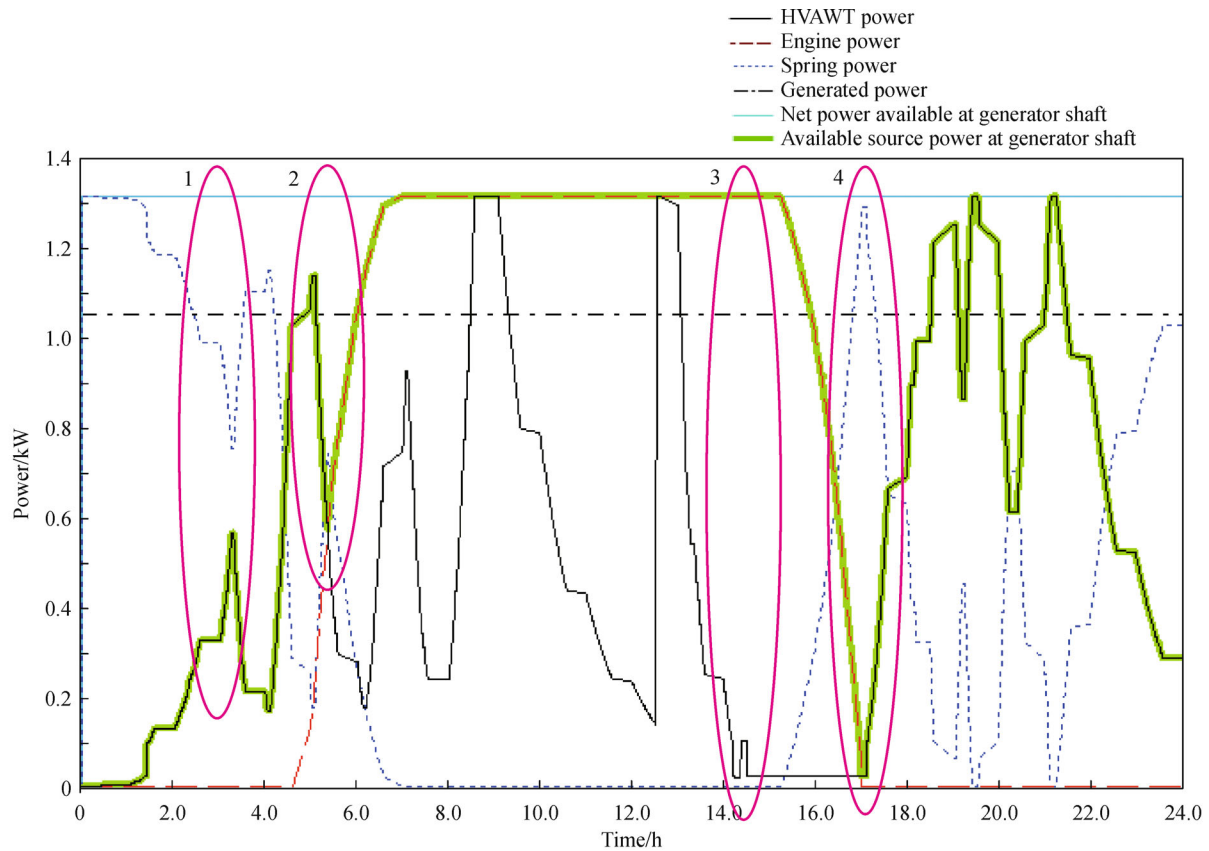


Fig. 8 Different powers yield in hybrid plant

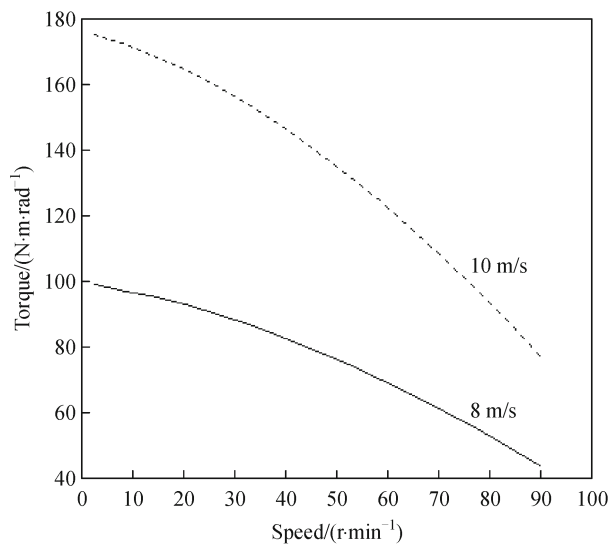


Fig. 9 Starting torque of HVAWT

maximum coefficient of power is obtained to be 0.3 against a TSR of 5. Further, it is perceived from the result that there is a 1% of reduction in the maximum power coefficient and a 0.75% of reduction in the optimal TSR for a 1% of decrease in the rated wind speed.

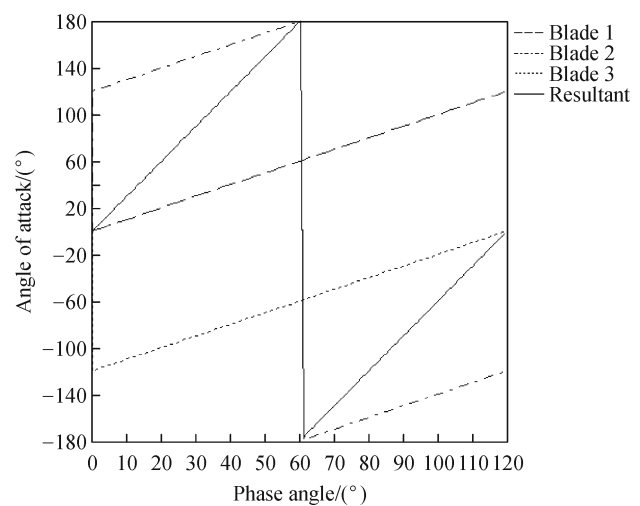


Fig. 10 Phase angle vs. angle of attack

3.5 Focal point temperature of Fresnel lens

The temperature at the focal point can be varied by varying its area, which helps in maintaining a constant temperature of the expansion chamber of the engine. The focal point temperature of two Fresnel lenses against the solar

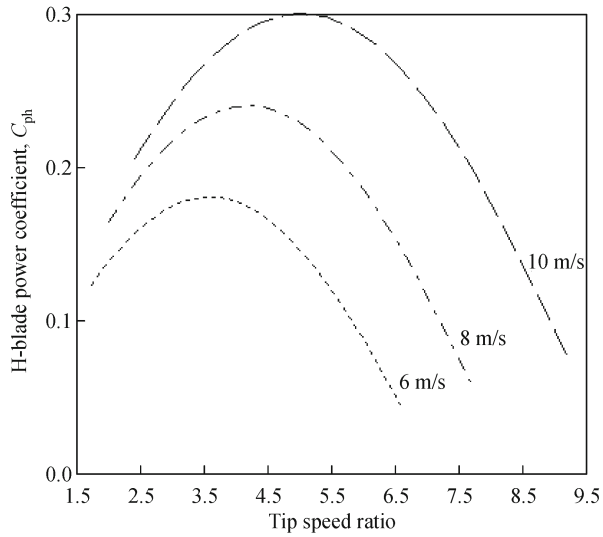


Fig. 11 Power coefficient variation of H-blade with TSR at different wind speed

insolation of 333 W/m^2 is shown in Fig. 12 where it is evidently observed that the temperature of the focal point is inversely proportional to its radius (R) for the same solar insolation. When solar insolation of 333 W/m^2 is concentrated by two 1 m^2 sized Fresnel lenses having a radius of 0.797 m and 0.564 m , the obtained temperature at the focal points are observed to be 2327.87 K and 2768.31 K , respectively.

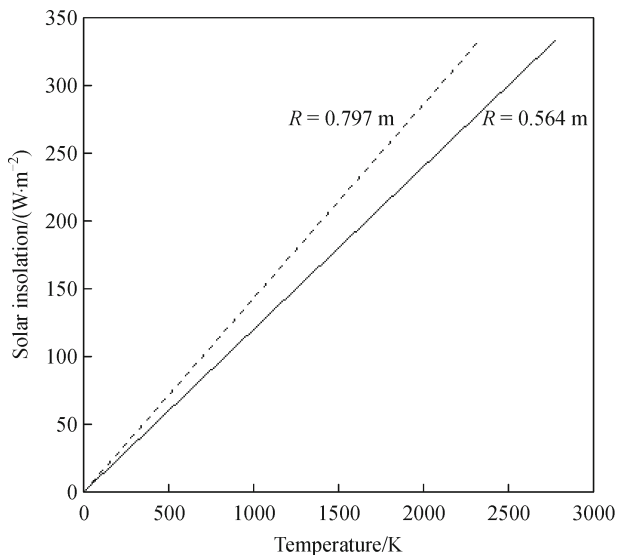


Fig. 12 Temperature variation with different focal point area of Fresnel lens

3.6 Torque-speed characteristic of Stirling engine

The power developed in the Stirling engine is the product

of its torque and rotational speed. Hence, for constant power, the torque varies inversely with the speed. The torque of the engine for the incremental speed from 20 r/min to 120 r/min at the rated power is shown in Fig. 13. From the torque-speed relationship, it is observed that the torque is reduced from $629.217 \text{ N}\cdot\text{m}$ to $104.87 \text{ N}\cdot\text{m}$. The parabolic shape of the curve signifies the nonlinearity in the torque reduction due to the enhancement in friction with the speed.

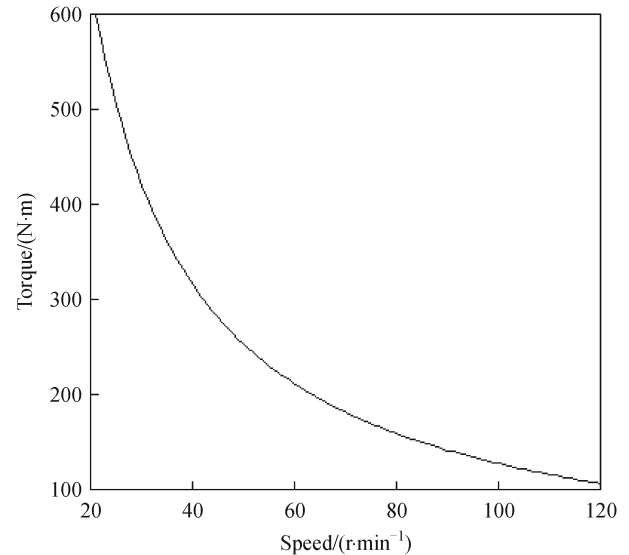


Fig. 13 Torque-speed characteristic of Stirling engine

4 Conclusions

Conventional energy sources are getting exhausted due to continuous increase in demand of power. The solar and wind energies are inexhaustible, universal, freely available and a green replacement of the conventional fuels.

This paper has described a hybridized wind-solar thermal power plant with a constant torque spring storage system. A 2.6 kW plant has been explained and various performance characteristics such as power production capability, starting torque of HVAWT, TSR vs. power coefficient of the H-blade, the torque speed characteristics of the Stirling engine etc. have been analyzed.

The torque in the HVAWT at the rated wind speed is found to be $178 \text{ N}\cdot\text{m/rad}$ in standstill condition and $76 \text{ N}\cdot\text{m/rad}$ when the turbine is rotating at a speed of 90 r/min . It is noticed that the power coefficient and optimal TSR declined at a rate of 1% and 0.75% when wind speed is reduced by 1% . The temperature at the focal point of Fresnel lens depends on its area and is found to be 2327.87 K and 2768.31 K for radius of 0.797 m and 0.564 m , respectively.

It has been observed from the results that the plant is capable of delivering constant output in spite of inter-

mittency of the sources. It can be concluded that the power plant has a great potential to operate as a base-load hybrid power station using renewable energy resources.

Notations

t	The ratio of compression temperature (T_c) and expansion temperature (T_e)
v	Ratio of swept volume of compression (V_{sc}) and swept volume of expansion (V_{se})
X_{de}	Ratio of dead volume of expansion (V_{de}) and swept volume of expansion (V_{se})
X_{dc}	Ratio of dead volume of compression (V_{dc}) and swept volume of expansion (V_{se})
X_r	Ratio of regenerator volume (V_r) and swept volume of expansion (V_{se})
a, b, c, S	Constants of the Stirling engine
D_x	Phase angle
W_e	Solar energy
i_s	Solar insolation
z	Time
M_g	Mass of working fluid
P_m	Mean engine pressure
R_f	Fluid constant
P_e	Engine pressure
W_i	Total work done in one complete cycle
W_e	Work done during expansion
W_c	Work done during compression
P_o	Output power of the engine
n	Speed of the engine
t_e	Stirling engine torque
T_l	Temperature at focal point of Fresnel lens
S	Stephen Boltzmann constant = $5.678 \times 10^{-8} \text{ W}/(\text{m}^4 \cdot \text{K}^4)$
A	Focal point area of lens

Coefficient of power for H-blade (C_{ph})	0.3
Radius of S-blade	2 m
Height of S-blade	2 m
Radius of H-blade	3 m
Height of H-blade	3 m

Solar thermal:

Sunrise time	4:30 am
Sunset time	5:00 pm
Total area of Fresnel lenses (L_a)	3 m^2
Working fluid	Air
Gas constant of air (R)	287 J/kgK
Fluid temperature of expansion (T_e)	500°C
Fluid temperature of compression (T_c)	30°C
Revolution of engine per minute (n)	1500
Crank angle (x) variation	0° to 360°
Phase angle (D_x)	90°
Regenerator volume (V_r)	0.2 cm^3
Swept volume of expansion space (V_{se})	500 cm^3
Swept volume of compression space (V_{sc})	500 cm^3
Dead volume of expansion space (V_{de})	0.2 cm^3
Dead volume of compression space (V_{dc})	0.2 cm^3

Storage spring:

Young's modulus (E)	200 GPa
Thickness (t_s)	2.794 mm
Width (b_s)	66.167 mm
Active length (L_t)	4.89 m
Natural radius of the spring (r_n)	101.6 mm
Radius of the outer spool (r_o)	220.98 mm

Alternator:

Type	Synchronous
Efficiency	80 %

Appendix Assumptions for different design parameters

Parameters	Assumptions
Wind system:	
Wind turbine	Hybrid vertical axis
Control method	Stall control
Number of blades	S-blade: 2 sets, H-blade: 3
Cut-in wind speed of S-blade	1.4 m/s
Cut-in speed of H-blade	4 m/s
Rated wind speed	10 m/s
Coefficient of power for S-blade (C_{ps})	0.18

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